

Sources for Metals in the Intergalactic Medium

Y.-Z. Qian¹ and G. J. Wasserburg²

ABSTRACT

We present a discussion of possible sources of C, O, and Si in the intergalactic medium (IGM) using the yields of very massive stars (VMSs) and Type II supernovae (SNe II). The chemical evolution of the IGM is considered based on analytical phenomenological models of hierarchical structure formation. Two regimes are considered: one for gas expulsion by VMSs and SNe II in low-mass halos prior to dissociation of H₂ molecules and reionization, and the other for later SN II-driven outflows from intermediate-mass halos. We use recent data on the abundances of C, O, and Si in the IGM inferred from two UV background (UVB) models. We show that the results from a UVB model including quasars only cannot be explained by existing stellar models. To account for the results, in particular $[\text{Si}/\text{C}]_{\text{IGM}}$, from a softer UVB model requires VMSs to provide $\gtrsim 15\%$ of the C in the IGM. The preferred scenario is that VMSs in low-mass halos provided between 15% and 60% of the C in the regime of very high redshift ($z \gtrsim 15$) and that galactic outflows provided the remainder during later epochs ($4 < z \lesssim 6$). Thus, there is a large gap in z between metal production by VMSs very early in the chemical evolution of the IGM and subsequent contributions from galactic outflows. The observational estimate of $[\text{O}/\text{H}]_{\text{IGM}}$ implies a high $[\text{Fe}/\text{H}]_{\text{IGM}} \geq -3$ for all cases considered (including the case of a pure VMS source). This raises problems with regard to observations of metal-poor stars in the Galaxy. In addition, the $[\text{O}/\text{Fe}]$ values for SN II models are in conflict with stellar observations, which indicate that the calculated average Fe yields of SNe II are a factor of ~ 2 too high. These issues and the general problem of relating abundances in the IGM to those in metal-poor stars remain to be investigated.

Subject headings: galaxies: formation — intergalactic medium — nuclear reactions, nucleosynthesis, abundances

¹School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455; qian@physics.umn.edu.

²The Lunatic Asylum, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125.

1. Introduction

We present a discussion of possible sources of C, O, and Si in the intergalactic medium (IGM) with particular consideration of very massive ($> 100 M_{\odot}$) stars (VMSs) and Type II supernovae (SNe II). It is now well established that there is a substantial inventory of metals in the general IGM over a wide range of redshift $z = 1.5$ – 5.5 (e.g., Songaila 2001; Pettini et al. 2003). Detailed studies of the data over $z = 1.8$ – 4.1 by Schaye et al. (2003) and Aguirre et al. (2004) show that at a given density the abundances of C and Si follow a lognormal distribution with substantial scatter. Both the median and the scatter of the distribution are dependent on the density but nearly independent of z . Using observations at $z \sim 2.5$ Simcoe, Sargent, & Rauch (2004) also found lognormal distributions for C and O. As only the ions C IV, O VI, and Si IV are directly measured, the inferred elemental abundances and in particular the relative abundances of C, O, and Si are sensitive to the model of UV background (UVB) used (e.g., Giroux & Shull 1997). We will use the results for two common UVB models adopted by the above two groups (see Table 1). For UVB model Q including quasars only, Schaye et al. (2003) found the average C abundance in the IGM to be $[C/H]_{\text{IGM}} \approx -2.3$ over the density range of the data used ($\log \delta = -0.5$ to 1.8 with δ being the density relative to the cosmic mean) and up to $[C/H]_{\text{IGM}} \approx -2.0$ when extrapolated to higher densities. The corresponding $[Si/C]_{\text{IGM}}$ is 1.45 (Aguirre et al. 2004). There is no evidence for evolution of either $[C/H]_{\text{IGM}}$ or $[Si/C]_{\text{IGM}}$ over $z = 1.8$ – 4.1 covered by the data. For a similar UVB model, Simcoe et al. (2004) found $[C/O]_{\text{IGM}} = 0$ and their lognormal distribution corresponds to $[C/H]_{\text{IGM}} = -2.2$. For a different UVB model QG including both quasars and galaxies, Schaye et al. (2003) and Aguirre et al. (2004) found $[C/H]_{\text{IGM}} = -2.8$ to -2.5 and $[Si/C]_{\text{IGM}} = 0.74$ while Simcoe et al. (2004) found $[C/O]_{\text{IGM}} = -0.5$ and a median abundance of $[C/H] = -3.1$, which would correspond to $[C/H]_{\text{IGM}} = -2.5$ for a lognormal distribution with the same scatter of 0.75 dex as for model Q. For both models Q and QG, the results of the two groups for $[C/H]_{\text{IGM}}$ are in good agreement. Note that model Q gives higher values for $[C/H]_{\text{IGM}}$ and much higher values for $[C/O]_{\text{IGM}}$ and $[Si/C]_{\text{IGM}}$ than model QG (see Table 1). Considering uncertainties in both the measurements and UVB models, the average abundances in the IGM are rather high with $[O/H]_{\text{IGM}} = -2.3$ to -2.0 . The C/O and Si/C ratios in the IGM do not appear to vary with density (Simcoe et al. 2004; Aguirre et al. 2004). Both $[C/H]_{\text{IGM}}$ and $[Si/C]_{\text{IGM}}$ appear to be independent of z over at least the range of $z = 1.8$ – 4.1 .

An important question is when the metal inventory of the IGM was provided. At present we know that this inventory was achieved prior to $z \sim 4$. Metal ejection from both low-mass ($\sim 10^5$ – $10^7 M_{\odot}$) halos at early epochs ($z \gtrsim 15$) and intermediate-mass ($\sim 10^8$ – $10^{10} M_{\odot}$) halos at later epochs ($z < 15$) will be discussed. The stellar sources of these metals are also not known but VMSs and SNe II are assumed to be the plausible candidates. We earlier

proposed a prompt metal inventory from VMSs (e.g., Wasserburg & Qian 2000). Using estimates of this inventory and yields of Heger & Woosley [2002 (HW)], Oh et al. (2001) suggested that VMSs could be the source of reionization (cf., Venkatesan & Truran 2003). It will be shown that if the IGM inventory was obtained at early epochs, the required metal production rate for VMSs and zero-metallicity SNe II in low-mass halos is much higher than the Galactic rate. In contrast, the bulk of the IGM inventory can be provided at later epochs by low-metallicity SNe II in intermediate-mass halos through efficient outflows for a Galactic metal production rate. However, in all cases and for all the stellar models considered there is a problem in accounting for the elemental ratios inferred for the IGM from UVB model Q. It will be shown that the ratios from model QG can be matched with significant contributions from VMSs. In particular, the Si/C ratio reported for the IGM appears to require a blend of contributions from both VMSs and SNe II if Salpeter initial mass functions (IMFs) are assumed for these sources.

We will not consider the contributions from intermediate-mass ($\sim 1\text{--}8 M_{\odot}$) stars in the following discussion. Such stars are thought to be an important source of C in the Galaxy on timescales of $\gtrsim 1$ Gyr, thereby contributing to the increase of [C/O] in Galactic stars from ~ -0.5 at $[\text{O}/\text{H}] \lesssim -1$ to ~ 0 at $[\text{O}/\text{H}] \sim 0$ (Akerman et al. 2004). Clearly, the delayed C contributions from intermediate-mass stars can be ignored for enrichment of the IGM at early epochs ($z \gtrsim 15$ or $\lesssim 0.26$ Gyr since the big bang). The precise epoch where intermediate-mass stars contribute to the IGM is not known. However, there is no evidence for evolution of either $[\text{C}/\text{H}]_{\text{IGM}}$ or $[\text{Si}/\text{C}]_{\text{IGM}}$ over at least the range of $z = 1.8\text{--}4.1$ (Schaye et al. 2003; Aguirre et al. 2004). Therefore, we will only consider VMSs and SNe II as the possible sources for metals in the IGM. As intermediate-mass stars produce C but no Si, the requirement of VMS contributions to account for the rather high $[\text{Si}/\text{C}]_{\text{IGM}}$ will be strengthened by any possible contributions from intermediate-mass stars.

2. Metal Ejection from Low-Mass Halos

We first explore the possibility that the metal inventory in the IGM is the result of astration (i.e., star formation) in low-mass ($\sim 10^5\text{--}10^7 M_{\odot}$) halos at $z \sim 15\text{--}30$. It is widely recognized that the first stars were formed in low-mass halos where gas could cool by H_2 molecules when the virial temperature T_{vir} reached ~ 300 K (e.g., Couchman & Rees 1986). Haiman, Rees, & Loeb (1997) showed that the soft UVB produced by the first massive stars could dissociate H_2 molecules in low-mass halos universally before the IGM was reionized. Dissociation of H_2 molecules drastically changes the condition for onset of astration to $T_{\text{vir}} \sim 10^4$ K as required for cooling by atomic species. This condition then governs astration for

all subsequent epochs including that of reionization. Ciardi, Ferrara, & Abel (2000) showed that universal H_2 dissociation has not yet taken place for $z \sim 20$. While the actual domain of astration by H_2 cooling remains to be established, we consider the regime of $z \sim 15\text{--}30$ to be within current estimates. Our purpose is to explore if such astration could possibly provide the metals in the IGM and what metal production rates are required to achieve this.

The nature of the first stars made of big bang debris is not known. They may be VMSs (see Abel, Bryan, & Norman 2003; Bromm & Larson 2004 for reviews). On the other hand, the discovery of a low-mass star with $[\text{Fe}/\text{H}] = -5.3$ (Christlieb et al. 2002) suggests that low-mass stars may have formed very early (e.g., Schneider et al. 2003) and presumably a broader spectrum of normal stars including SN II progenitors might be expected for the first stars. In either case, the occurrence of a VMS or SN II in a low-mass halo would disrupt the baryonic gas in the halo and disperse it into the IGM on some scale. To estimate the range of low-mass halos with gas expulsion, we use models of hierarchical structure formation in the standard cold dark matter cosmology as discussed in Barkana & Loeb (2001).

A critical parameter for halo evolution is the virial temperature T_{vir} of the gas. For $z > 1$, T_{vir} is related to the halo mass M (mostly in dark matter) as

$$T_{\text{vir}} \approx 211 \left(\frac{\mu}{1.22} \right) \left(\frac{M}{10^5 M_{\odot}} \right)^{2/3} \left(\frac{1+z}{10} \right) \text{ K}, \quad (1)$$

where μ is the mean atomic weight and $\mu = 1.22$ or 0.6 for a neutral or ionized gas, respectively, with a primordial composition of H and He. We assume that astration starts when the gas reaches a threshold virial temperature $T_{\text{vir},0}$ for cooling. For H_2 cooling we will take $T_{\text{vir},0} = 300 \text{ K}$ ($\mu = 1.22$). Another critical parameter is the gas binding energy $E_{\text{bi,gas}}$. For $z > 1$,

$$E_{\text{bi,gas}} \approx 4.31 \times 10^{47} \left(\frac{M}{10^5 M_{\odot}} \right)^{5/3} \left(\frac{1+z}{10} \right) \text{ erg}. \quad (2)$$

We assume that all the gas would be expelled from the halo by an SN II or VMS with an explosion energy E_{exp} if $E_{\text{bi,gas}} < E_{\text{exp}}$ (e.g., Bromm, Yoshida, & Hernquist 2003) and retained for $E_{\text{bi,gas}} \geq E_{\text{exp}}$. For illustration, we take $E_{\text{exp}} = 10^{51} \text{ erg}$ for SNe II and $4 \times 10^{52} \text{ erg}$ for VMSs (HW).

For a halo associated with an $n\sigma$ density fluctuation (an $n\sigma$ halo), the growth of its mass $M(z)$ as a function of z is prescribed by the Press-Schechter formalism (Press & Schechter 1974; see Fig. 6 in Barkana & Loeb 2001). Astration starts in a 3σ halo when the halo mass reaches $M_0 = 3.6 \times 10^4 M_{\odot}$ at $z = 26.9$. The gas in the halo would be expelled by an SN II until the halo mass grows to $M_{\text{bi}} = 7.0 \times 10^6 M_{\odot}$ at $z = 18.6$ or by a VMS until $M_{\text{bi}} = 7.1 \times 10^7 M_{\odot}$ at $z = 15.3$. In general, at a given z an $n_0\sigma$ halo would reach $M(z) = M_0$

to start astration and an $n_{\text{bi}}\sigma$ halo would reach $M(z) = M_{\text{bi}}$ to greatly hinder gas expulsion. At any given z all $n\sigma$ halos with $n_0 < n < n_{\text{bi}}$ corresponding to $M_0 < M < M_{\text{bi}}$ have started astration but will be disrupted by an SN II or VMS. The relevant range of halos at $z = 20$ corresponds to $2.3 < n < 3.2$ ($5.5 \times 10^4 M_\odot < M < 6.7 \times 10^6 M_\odot$) for SNe II or $2.3 < n < 3.8$ ($5.5 \times 10^4 M_\odot < M < 6.1 \times 10^7 M_\odot$) for VMSs. For a given z , the fraction $F(M_0 < M < M_{\text{bi}}|z)$ of all matter in $n\sigma$ halos with $n_0 < n < n_{\text{bi}}$ is

$$F(M_0 < M < M_{\text{bi}}|z) = \sqrt{\frac{2}{\pi}} \int_{n_0}^{n_{\text{bi}}} \exp\left(-\frac{x^2}{2}\right) dx. \quad (3)$$

The function $F(M_0 < M < M_{\text{bi}}|z)$ for $T_{\text{vir},0} = 300$ K and $E_{\text{bi,gas}} = 10^{51}$ erg is very close to that for the same $T_{\text{vir},0}$ but $E_{\text{bi,gas}} = 4 \times 10^{52}$ erg as halos with $E_{\text{bi,gas}} > 10^{51}$ erg are extremely rare for $z > 15$. A fraction $\sim 0.05\%$ to 5% of all matter is in low-mass halos with gas expulsion at $z = 30$ to 15 .

We now estimate enrichment of the IGM by gas expulsion from low-mass halos using O as a representative element. We consider a large reference region of the universe and treat it as a closed homogeneous system. We assume that the expelled gas is immediately mixed with the entire IGM of the reference region. In this case, the number ratio $(\text{O}/\text{H})_{\text{IGM}}$ of O to H atoms in the IGM as a function of time t (since the big bang) is determined by

$$\frac{d(\text{O}/\text{H})_{\text{IGM}}}{dt} = \sum_{n=n_0}^{n_{\text{bi}}} P_{\text{O},n\sigma}/(\text{H})_{\text{IGM}}, \quad (4)$$

where $P_{\text{O},n\sigma}$ is the O production rate in an $n\sigma$ halo and the sum extends over all the $n\sigma$ halos with $n_0 < n < n_{\text{bi}}$ in the reference region. We explicitly assume that $P_{\text{O},n\sigma}$ is proportional to the number $(\text{H})_{n\sigma}$ of H atoms in the gas of the $n\sigma$ halo,

$$P_{\text{O},n\sigma} = \Lambda_{\text{O}}(\text{O}/\text{H})_\odot (\text{H})_{n\sigma}. \quad (5)$$

For $z \gg 1$, the majority of the H atoms in the reference region reside in the IGM and the majority of the H atoms in a halo reside in the gas. This gives

$$\frac{d(\text{O}/\text{H})_{\text{IGM}}}{dt} \approx \Lambda_{\text{O}}(\text{O}/\text{H})_\odot F(M_0 < M < M_{\text{bi}}|z). \quad (6)$$

The constant parameter Λ_{O} is related to the frequency of occurrence (R) for the O source in a halo of mass M as

$$R = \Lambda_{\text{O}} X_{\text{O}}^\odot \frac{f_b M}{\langle Y_{\text{O}} \rangle} = 144 \Lambda_{\text{O}} \left(\frac{M_\odot}{\langle Y_{\text{O}} \rangle} \right) \left(\frac{M}{10^5 M_\odot} \right), \quad (7)$$

where $X_{\text{O}}^{\odot} = 9.6 \times 10^{-3}$ is the solar mass fraction of O, $f_b = 0.15$ is the baryonic mass fraction for the halo, and $\langle Y_{\text{O}} \rangle$ is the average O yield of the source. Equation (6) can be integrated to give

$$Z_{\text{O}}^{\text{IGM}} \equiv \frac{(\text{O}/\text{H})_{\text{IGM}}}{(\text{O}/\text{H})_{\odot}} = \Lambda_{\text{O}} \int_0^{t(z)} F(M_0 < M < M_{\text{bi}}|z') dt', \quad (8)$$

where $t(z) = 0.538[10/(1+z)]^{3/2}$ Gyr for the adopted cosmology and $t' \equiv t(z')$. The above treatment is readily extended to mixtures from different sources.

The result for $[\text{O}/\text{H}]_{\text{IGM}} = \log Z_{\text{O}}^{\text{IGM}}$ as a function of z is shown in Figure 1 for $\Lambda_{\text{O}} = 0.1 \text{ Gyr}^{-1}$ using $T_{\text{vir},0} = 300 \text{ K}$ for M_0 and $E_{\text{bi,gas}} = 10^{51} \text{ erg}$ for M_{bi} (solid curve). Replacing the mass range $M_0 < M < M_{\text{bi}}$ with $M > 10^5 M_{\odot}$ gives essentially the same result (dot-dashed curve). The rate $\Lambda_{\text{O}} = 0.1 \text{ Gyr}^{-1}$ is representative of O production by SNe II in the Galaxy [the solar O abundance is produced by SNe II over $\sim 10 \text{ Gyr}$]. For this rate $[\text{O}/\text{H}]_{\text{IGM}} = -3.5$ at $z = 15$. So SNe II in low-mass halos cannot provide the IGM inventory with a nominal abundance of $[\text{O}/\text{H}]_{\text{IGM}} = -2.3$ unless the relevant production rate is 16 times higher than the Galactic rate. The requirement of $\Lambda_{\text{O}} = 1.6 \text{ Gyr}^{-1}$ would also apply to any other sources (including VMSs) if they were to produce the IGM inventory at early epochs. Simulations by Norman, O’Shea, and Paschos (2004) appear to suggest that VMSs could not enrich the IGM to the level of $[\text{O}/\text{H}]_{\text{IGM}} = -2.3$. However, this result was based on putting one VMS in each halo with $M \geq 5 \times 10^5 M_{\odot}$ that was found in a simulation volume of 1 Mpc^3 at $z = 15$. The number of such halos found in the simulation volume may not be statistically representative (M. L. Norman, personal communication). Future numerical studies on early enrichment of the IGM by VMSs or any other sources should use larger simulation volumes to check the required metal production rate against the value given here.

3. Galactic Outflows

We next consider contributions to the IGM from just galactic outflows at $z < 15$. We assume that only normal stars including SNe II progenitors are formed and astration starts when $T_{\text{vir},0} = 10^4 \text{ K}$ ($\mu = 0.6$) is reached for cooling by atomic species. The halo mass at the onset of astration ranges from $M_0 = 4.6 \times 10^7 M_{\odot}$ for $z = 15$ to $2.6 \times 10^8 M_{\odot}$ for $z = 4$. For these masses $E_{\text{bi,gas}} > 10^{51} \text{ erg}$ so an SN II cannot expel all the gas from the halo. Subsequent to the onset of astration, we assume that a fraction ϵ of the metals produced by SNe II is lost from the halo and injected broadly into the IGM until the halo reaches a cutoff mass M_1 . While the dependence of ϵ on the halo mass may be complicated, we will treat it as a constant to determine how efficient mass loss must be to provide the IGM inventory

prior to $z = 4$. Applying the same formalism leading to equation (8), we have

$$Z_{\text{O}}^{\text{IGM}} = \epsilon \Lambda_{\text{O}} \int_{t_{15}}^{t(z)} F(M_0 < M < M_1 | z') dt', \quad (9)$$

where $t_{15} = 0.26$ Gyr is the time corresponding to $z = 15$. Using $\Lambda_{\text{O}} = 0.1 \text{ Gyr}^{-1}$ and $\epsilon = 0.1$, we show $[\text{O}/\text{H}]_{\text{IGM}} = \log Z_{\text{O}}^{\text{IGM}}$ as a function of z for $M_1 = 10^9$ and $10^{10} M_{\odot}$ (short and long dashed curves), respectively, in Figure 1. These M_1 values are consistent with observations of outflows from Lyman break and dwarf galaxies (e.g., Pettini et al. 2001; Martin, Kobulnicky, & Heckman 2002). Values of $M_1 > 10^{10} M_{\odot}$ give almost the same result as $M_1 = 10^{10} M_{\odot}$. Figure 1 gives $[\text{O}/\text{H}]_{\text{IGM}} = -2.9$ at $z = 4$ for $M_1 = 10^{10} M_{\odot}$. Thus to achieve $[\text{O}/\text{H}]_{\text{IGM}} = -2.3$ at $z = 4$ by just galactic outflows requires a rather high but still reasonable $\epsilon = 0.4$ for a Galactic metal production rate of $\Lambda_{\text{O}} = 0.1 \text{ Gyr}^{-1}$ or an equivalent $\epsilon \Lambda_{\text{O}} = 0.04 \text{ Gyr}^{-1}$. Obviously, smaller values of $\epsilon \Lambda_{\text{O}}$ are required if galactic outflows are to provide some significant portions but not all of the IGM inventory (see §4).

4. Elemental Ratios in the IGM and Implications for the Sources

The results for $Z_{\text{O}}^{\text{IGM}}$ in §§2 and 3 can be extended to other elements using the relevant production rates. For two elements E and E',

$$\frac{Z_{\text{E}}^{\text{IGM}}}{Z_{\text{E}'}^{\text{IGM}}} = \frac{\Lambda_{\text{E}}}{\Lambda_{\text{E}'}} = \frac{\langle Y_{\text{E}} \rangle}{\langle Y_{\text{E}'} \rangle} \left(\frac{X_{\text{E}'}^{\odot}}{X_{\text{E}}^{\odot}} \right), \quad (10)$$

where

$$\langle Y_{\text{E}} \rangle = \frac{\int_{m_l}^{m_u} Y_{\text{E}}(m) \phi(m) dm}{\int_{m_l}^{m_u} \phi(m) dm}. \quad (11)$$

In the above equation m is the mass in units of M_{\odot} for the source with m_l and m_u being the lower and upper limits, $Y_{\text{E}}(m)$ is the yield of element E as a function of m , and $\phi(m) = m^{-\beta}$ is the IMF. We assume a Salpeter IMF ($\beta = 2.35$) for SNe II. As there is no a priori knowledge on the mass distribution of VMSs, a wide range of IMFs with $\beta = 2.35, 10$, and 20 are explored. This allows us to examine a wide range of abundance ratios of Si and Fe relative to C and O resulting from VMS sources. The average yields $\langle Y_{\text{E}} \rangle$ for C, O, Si, and Fe and the corresponding $[\text{C}/\text{O}]$, $[\text{Si}/\text{C}]$, and $[\text{O}/\text{Fe}]$ are given in Table 2 for a number of models of VMSs [Umeda & Nomoto 2002 (UN); HW] and SNe II [Woosley & Weaver 1995 (WW); UN; Chieffi & Limongi 2004 (CL)] for the β values considered. Clearly, the elemental ratio E/E' for a source only depends on those stars with finite yields of E and E'. For this reason, we give the limiting masses for metal production as m_l and m_u in Table 2. Although some

VMSs or SNe II may form outside this mass range, they do not affect the calculation of the elemental ratios.

Table 2 shows that VMSs have a narrow range of $[C/O] = -0.71$ to -0.50 for a wide range of IMFs but their $[Si/C]$ varies from 1.18–1.30 for a Salpeter IMF to 0.61–0.84 for an IMF with $\beta = 20$ that very strongly favors the lower masses. This is because the C and O yields are nearly constant for all contributing VMSs while the Si yield increases significantly (the Fe yield increases steeply) with mass (UN; HW). In contrast, models of zero-metallicity SNe II (WW; UN; CL) give narrow ranges of $[C/O] = -0.23$ to 0.02 and $[Si/C] = 0.13$ – 0.17 . For SNe II with very low to solar metallicities, WW give $[C/O] = -0.42$ and $[Si/C] = 0.42$ – 0.50 while CL give $[C/O] = -0.2$ and $[Si/C] = 0.18$ – 0.28 . We consider that SNe II in the regime of low metallicities are relevant to the problem at hand. In all cases, $[Si/C]$ is high for VMSs but low for SNe II with zero or low metallicities. It is the high value of $[Si/C]_{IGM}$ that indicates significant VMS contributions as noted by Aguirre et al. (2004) (see also Schaerer 2002). As VMSs have $[Si/C] \gtrsim [Si/C]_{IGM}$ while SNe II have $[Si/C] < [Si/C]_{IGM}$, this supports the existence of VMS contributions but was not discussed in the recent critique of VMS models by Tumlinson, Venkatesan, and Shull (2004).

We first compare the elemental ratios from stellar models with $[C/O]_{IGM} = 0$ and $[Si/C]_{IGM} = 1.45$ inferred from UVB model Q. Neither VMSs nor SNe II of any metallicity can account for both $[C/O]_{IGM}$ and $[Si/C]_{IGM}$. As $[C/O]$ is close to $[C/O]_{IGM}$ for SNe II of zero metallicity (or all metallicities according to CL) and $[Si/C]$ is close to $[Si/C]_{IGM}$ for VMSs with a Salpeter IMF, one may consider a mixture from these two sources. However, to approximately match $[C/O]_{IGM}$ would require that almost all of the C come from SNe II and this would give a $[Si/C]$ for the mixture essentially equal to the SN II value, which is off by > 1 dex from the IGM value. Similarly, matching $[Si/C]_{IGM}$ would require that almost all of the C come from VMSs, thus giving a very low $[C/O]$ for the mixture. So in all cases and for all the stellar models there is a problem in accounting for the elemental ratios inferred from UVB model Q.

We now consider UVB model QG with $[C/O]_{IGM} = -0.5$ and $[Si/C]_{IGM} = 0.74$. These ratios cannot be matched by VMSs with a Salpeter IMF, for which $[Si/C] \geq 1.18$. A match can be obtained for VMSs if an IMF very strongly favoring the lower masses is used (see models 2B, 1C, and 2C in Table 2). It is also possible to obtain a match with both $[C/O]_{IGM}$ and $[Si/C]_{IGM}$ for UVB model QG if we consider mixtures of VMS and SN II contributions. As the largest $[Si/C] = 1.3$ for VMSs (model 1A) and the largest $[Si/C] = 0.42$ for SNe II of low metallicity (model 6), to match $[Si/C]_{IGM} = 0.74$ requires a fraction of at least $f_C^{VMS} = 0.16$ of the C to come from VMSs. Below we discuss four representative cases, all of which match $[C/O]_{IGM}$ and $[Si/C]_{IGM}$ for UVB model QG to within 0.1 dex (see Table 3).

In case I the IGM inventory was produced by just VMSs (IMF with $\beta = 20$) in low-mass halos at early epochs ($z \gtrsim 15$). A high metal production rate of $\Lambda_{\text{O}}^{\text{VMS}} = 1.6 \text{ Gyr}^{-1}$ is required to achieve $[\text{O}/\text{H}]_{\text{IGM}} = -2.3$ (§2). This corresponds to a frequency of occurrence $R_{\text{VMS}} = 4(M/10^5 M_{\odot}) \text{ Gyr}^{-1}$ (eq. [7] for $\langle Y_{\text{O}}^{\text{VMS}} \rangle = 54.3 M_{\odot}$) so that every halo of $\sim 10^5 M_{\odot}$ would have formed ~ 1 VMS by $z = 15$ ($t_{15} = 0.26 \text{ Gyr}$). This rate is usually considered the upper limit for VMS formation as the UV irradiation from a VMS suppresses further star formation in its hosting halo (e.g., Couchman & Rees 1986). Case I does not allow any significant contributions to the IGM from galactic outflows at later epochs ($z < 15$). This appears to be in conflict with observations of outflows from Lyman break and dwarf galaxies (e.g., Pettini et al. 2001; Martin et al. 2002). It is also at odds with the attribution of the bulk of the IGM inventory to galactic outflows as advocated by many previous studies (e.g., Madau, Ferrara, & Rees 2001; Scannapieco, Ferrara, & Madau 2002; Thacker, Scannapieco, & Davis 2002). In addition, Bromm & Loeb (2003) suggested that VMSs may form only for metallicities below $[\text{C}/\text{H}] = -3.5 \pm 0.1$ and $[\text{O}/\text{H}] = -3.0 \pm 0.2$. However, for case I VMSs are required to provide $[\text{C}/\text{H}] = -2.9$ and $[\text{O}/\text{H}] = -2.3$, which are much beyond the suggested termination point for their formation.

In case II the sources for metals in the IGM are a combination of VMSs and zero-metallicity SNe II in low-mass halos at early epochs. A single Salpeter IMF ($\beta = 2.35$) is used for the mass range covering both VMSs and SNe II. To achieve $[\text{O}/\text{H}]_{\text{IGM}} = -2.3$ requires $\Lambda_{\text{O}}^{\text{VMS}} = 0.9 \text{ Gyr}^{-1}$ and $\Lambda_{\text{O}}^{\text{SNII}} = 0.7 \text{ Gyr}^{-1}$. The latter is 7 times greater than the Galactic value. Thus case II requires high metal production rates for both VMSs and zero-metallicity SNe II. As in case I, case II does not allow significant contributions from galactic outflows and requires VMSs to provide enrichments beyond the suggested termination point for their formation.

For cases III and IV we consider a combination of early contributions from VMSs (IMF with $\beta = 10$ for case III and Salpeter IMF for case IV) and later galactic outflows driven by low-metallicity SNe II. Case III is chosen to match $[\text{Si}/\text{C}]_{\text{IGM}} = 0.74$ exactly. The required rate of $\Lambda_{\text{O}}^{\text{VMS}} = 1.0 \text{ Gyr}^{-1}$ is high but the required galactic outflows with an efficiency of $\epsilon = 0.1$ for a Galactic rate of $\Lambda_{\text{O}}^{\text{SNII}} = 0.1 \text{ Gyr}^{-1}$ (for $M_1 = 10^{10} M_{\odot}$, see §3) are quite reasonable. Case III also requires VMSs to provide $[\text{C}/\text{H}] = -3.0$ and $[\text{O}/\text{H}] = -2.5$, which are in excess of the termination metallicities for their formation as suggested by Bromm & Loeb (2003). Case IV was calculated using $f_{\text{C}}^{\text{VMS}} = 0.15$, which requires VMSs to provide metals only up to the suggested termination point, and hence, a much smaller rate of $\Lambda_{\text{O}}^{\text{VMS}} = 0.3 \text{ Gyr}^{-1}$. The required efficiency of galactic outflows is $\epsilon = 0.3$ for a Galactic $\Lambda_{\text{O}}^{\text{SNII}}$. If we instead had required an exact match to $[\text{Si}/\text{C}]_{\text{IGM}}$ for case IV, then $f_{\text{C}}^{\text{VMS}} = 0.23$ with no major difference in the results.

The results in Table 3 show that VMSs must be significant contributors to the IGM based on the $[\text{Si}/\text{C}]_{\text{IGM}}$ value and that either a pure VMS source with an extreme IMF or a blend of VMS and SN II sources could provide the observed metal inventory in the IGM. However, case IV appears to be the best scenario if we require (1) major contributions from galactic outflows, (2) a Galactic $\Lambda_{\text{O}}^{\text{SNII}}$, (3) a nonextreme IMF for VMSs, and (4) strict termination metallicities for VMS formation as suggested by Bromm & Loeb (2003). In case IV VMSs in low-mass halos provided 15% of the C, 20% of the O, and 51% of the Si prior to H_2 dissociation and reionization, and the rest of the IGM inventory was provided by later efficient outflows driven by SNe II in intermediate-mass halos. This suggests that VMSs must be substantial contributors to the IGM with high frequencies of occurrences at very high z . Venkatesan & Truran (2003) calculated that VMSs would provide 10 H-ionizing photons per baryon in order to reach $[\text{O}/\text{H}]_{\text{IGM}} = -2.5$. So the VMSs in case IV would provide ≈ 3 H-ionizing photons per baryon in reaching $[\text{O}/\text{H}] = -3.0$ (using C gives the same result. Note that the value of 0.35 H-ionizing photons per baryon given in Venkatesan & Truran 2003 assumes a termination metallicity of $[\text{O}/\text{H}] \sim -4.0$ for VMS formation). This may be consistent with the “weak” version of the VMS scenario discussed in Tumlinson et al. (2004).

So far our discussion has focused on C, O, and Si as these elements are measured in the IGM. The abundances of other elements such as Fe can also be calculated for the four cases discussed above. The O and Fe yields in Table 2 give $[\text{O}/\text{Fe}] = 0.71$ and 0.52 for cases I and III, respectively, and $[\text{O}/\text{Fe}] = 0.12$ for cases II and IV (see Table 3). For $[\text{O}/\text{H}]_{\text{IGM}} = -2.3$, this implies $[\text{Fe}/\text{H}]_{\text{IGM}} = -3.0$ and -2.8 for cases I and III, respectively, and $[\text{Fe}/\text{H}]_{\text{IGM}} = -2.4$ for cases II and IV. Observations of metal-poor stars in the Galaxy (e.g., Cayrel et al. 2004) show that $[\text{O}/\text{Fe}] \gtrsim 0.5$ for $[\text{Fe}/\text{H}] \sim -3.0$ to -2.4 . Cases I and III are consistent with these observations. However, the $[\text{O}/\text{Fe}]$ value for cases II and IV is too low compared with those observed in metal-poor stars. This may be a potentially important problem for these two cases, especially for case IV, which satisfies all the other criteria discussed above. The low $[\text{O}/\text{Fe}]$ value for cases II and IV is mostly due to the low values of $[\text{O}/\text{Fe}] \sim 0.2$ given by SN II models. We note that the Fe yields of SNe II were not calculated a priori but generated by employing largely artificial mass cuts in all models. Stellar observations (e.g., Nissen et al. 2002) show that $[\text{O}/\text{Fe}] \sim 0.5$ for the regime of $-2.4 < [\text{Fe}/\text{H}] < -1.5$, where SNe II are clearly the dominant source for both O and Fe. This indicate that the calculated average Fe yields of SNe II are a factor of ~ 2 too high. Much work is required to resolve the problem of Fe yields and the associated uncertainties in $[\text{O}/\text{Fe}]$ for SN II models. We also note that our next best case III gives an adequate $[\text{O}/\text{Fe}]$ but requires VMSs to provide $[\text{C}/\text{H}]$ and $[\text{O}/\text{H}]$ somewhat beyond the termination metallicities suggested by Bromm & Loeb (2003). If the criteria for termination

of VMS formation could be relaxed, then case III may be a viable alternative to case IV in accounting for the IGM data and stellar observations.

Clearly, the results presented here are subject to uncertainties in theoretical models of stellar yields and in IGM measurements and analyses. Possible uncertainties are unlikely to explain the large discrepancies between stellar models and the elemental ratios from UVB model Q but may affect some of our results regarding model QG. As discussed above, uncertainties in Fe yields of SN II models affect the $[\text{O}/\text{Fe}]$ values for cases II and IV. In addition, the required rates quoted above (see Table 3) correspond to a nominal abundance of $[\text{O}/\text{H}]_{\text{IGM}} = -2.3$ and would change if different values were used. For this nominal value all four cases considered (including case I for a pure VMS source) imply $[\text{Fe}/\text{H}]_{\text{IGM}} \geq -3.0$ (using $[\text{O}/\text{Fe}] = 0.5$ instead of 0.12 for cases II and IV does not change the result). This is high considering a number of ultra-metal-poor stars in the Galaxy have $-4 \lesssim [\text{Fe}/\text{H}] < -3$ (e.g., Christlieb 2003). One possible explanation would be that those ultra-metal-poor stars formed in small halos in under-enriched regions and were later accreted into the Galaxy. This is consistent with the large scatter for the lognormal distribution of metal abundances in the IGM and with the standard model of hierarchical structure formation. The above issues and the general problem of relating abundances in the IGM to those in metal-poor stars remain to be addressed.

In summary, we find that VMSs must be significant contributors to the IGM. Our preferred scenario is that VMSs provided between 15% (case IV) and 60% (case III) of the C (and corresponding levels of other metals) in the IGM by disrupting the gas in low-mass ($\sim 10^5\text{--}10^7 M_\odot$) halos at very high redshift ($z \gtrsim 15$). Outflows driven by SNe II in intermediate-mass ($\sim 10^8\text{--}10^{10} M_\odot$) halos provided the remainder (the bulk in case IV) of the metals during later epochs ($4 < z \lesssim 6$, see Fig. 1). Thus, there is a large gap in z between metal production by VMSs very early in the chemical evolution of the IGM and subsequent contributions from galactic outflows. The metals from these two different sources appear to be well mixed locally but have a wide range in net abundances as established by Schaye et al. (2003), Aguirre et al. (2004), and Simcoe et al. (2004).

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Table 1. IGM Data^a

UVB Model	[O/H] _{IGM}	[C/O] _{IGM}	[Si/C] _{IGM}
Q	−2.3 to −2.0	0	1.45
QG	−2.3 to −2.0	−0.5	0.74

^a[C/O]_{IGM} from Simcoe et al. 2004, [Si/C]_{IGM} from Aguirre et al. 2004, and [O/H]_{IGM} from Simcoe et al. 2004 or converted from [C/H]_{IGM} of Schaye et al. 2003 using [C/O]_{IGM}. Solar abundances adopted: $\log \epsilon_{\odot}(\text{C}) = \log(\text{C}/\text{H})_{\odot} + 12 = 8.52$, $\log \epsilon_{\odot}(\text{O}) = 8.83$ (Grevesse & Sauval 1998), and $\log \epsilon_{\odot}(\text{Si}) = 7.55$ (Anders & Grevesse 1989).

Table 2. VMS and SN II Yields and Yield Ratios

Metallicity			$\langle Y_{\text{E}} \rangle (M_{\odot})$							
Model	(Z/Z_{\odot})	(m_l, m_u)	β	C	O	Si	Fe	[C/O] ^a	[Si/C] ^a	[O/Fe] ^b
VMSs										
1A (UN)	0	(150, 270)	2.35	3.67	51.0	18.4	6.85	−0.71	1.30	0.00
2A (HW)	0	(140, 260)	2.35	4.34	44.2	16.6	6.21	−0.57	1.18	−0.02
1B (UN)	0	(150, 270)	10	4.56	52.4	12.7	2.99	−0.62	1.05	0.38
2B (HW)	0	(140, 260)	10	4.99	46.4	9.24	0.67	−0.53	0.87	0.97
1C (UN)	0	(150, 270)	20	5.41	54.3	9.41	1.42	−0.57	0.84	0.71
2C (HW)	0	(140, 260)	20	5.51	47.2	5.59	0.046	−0.50	0.61	2.14
SNe II										
3 (WW)	0	(12, 30)	2.35	0.12	0.30	0.039	0.099	0.02	0.13	−0.38
4 (UN)	0	(13, 30)	2.35	0.28	1.29	0.098	0.083	−0.23	0.15	0.32
5 (CL)	0	(13, 35)	2.35	0.31	1.19	0.11	0.10	−0.15	0.17	0.19
6 (WW)	0.01	(12, 40)	2.35	0.20	1.43	0.13	0.13	−0.42	0.42	0.17
7 (CL)	0.005	(13, 35)	2.35	0.34	1.49	0.13	0.10	−0.21	0.18	0.28
8 (WW)	1	(11, 40)	2.35	0.19	1.37	0.15	0.12	−0.42	0.50	0.20
9 (CL)	1	(15, 35)	2.35	0.36	1.54	0.17	0.14	−0.20	0.28	0.19

^aCalculated using the same solar abundances as in Table 1.

^bCalculated using $X_{\text{O}}^{\odot} = 9.6 \times 10^{-3}$ and $X_{\text{Fe}}^{\odot} = 1.3 \times 10^{-3}$ (Anders & Grevesse 1989).

Table 3. Representative Cases to Match the IGM Data from UVB Model QG

Case	VMS Model	SN II Model	f_C^{VMSa}	[C/O]	[Si/C]	f_O^{VMSa}	[O/Fe]	Λ_O^{VMS} (Gyr ⁻¹) ^b	Λ_O^{SNII} (Gyr ⁻¹) ^b	ϵ^b
I	1C	...	1	-0.57	0.84	1	0.71	1.6
II	1A	4	0.28	-0.42	0.82	0.54	0.12	0.9	0.7	...
III	2B	6	0.60	-0.49	0.74	0.66	0.52	1.0	0.1	0.1
IV	2A	6	0.15	-0.45	0.65	0.20	0.12	0.3	0.1	0.3

^aSpecified by the same Salpeter IMF governing both VMSs and SNe II for case II, chosen to match [Si/C] = -0.74 exactly for case III, and chosen to obtain [O/H] = -3.0 from VMSs for case IV.

^bRates and efficiencies required to provide [O/H] = -2.3. The required rate Λ_O^{VMS} for VMSs in all cases and the required rate Λ_O^{SNII} for zero-metallicity SNe II in case II are given assuming complete disruption of the gas by these sources in low-mass halos. For galactic outflows in cases III and IV, the required outflow efficiency ϵ is given assuming a Galactic Λ_O^{SNII} (an equivalent $\epsilon\Lambda_O^{\text{SNII}}$ also satisfies the requirement).

Fig. 1.— Evolution of $[O/H]_{\text{IGM}}$ as a function of z for gas expulsion from low-mass halos with astration controlled by H_2 cooling (solid curve for contributing halos with $M_0 < M < M_{\text{bi}}$ determined by $T_{\text{vir},0} = 300$ K for onset of astration and $E_{\text{bi,gas}} = 10^{51}$ erg for onset of gas retention, dot-dashed curve for contributing halos with $M > 10^5 M_{\odot}$) or outflows from intermediate-mass halos subsequent to H_2 dissociation ($T_{\text{vir},0} = 10^4$ K, short and long-dashed curves for cutoff masses of 10^9 and $10^{10} M_{\odot}$, respectively). The vertical line at $z = 15$ divides the two regimes. For both regimes the reference production rate $\Lambda_O = 0.1 \text{ Gyr}^{-1}$ corresponds to the Galactic rate for SNe II.

